Model of radiowaves dispertion in atmosphere.

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1. ABSTRACT

Physical aspects of dispersion (dependence of refraction factor value from frequency) emergence in case of radiowave propagation in atmosphere with nonlinear dependence of atmosphere refraction factor value from coordinates have been considered. Dispertion phenomenologic model proved by results of nature measurements in surface millimeter range direct visibility radioline has been put forward.

2. INTRODUCTION

The dispertion of atmosphere (dependence of atmosphere refraction factor n from frequency ω) is a fundamental cause limiting communication systems passband, location systems operation accuracy, etc. The most urgent dispersion data is related to the millimeter radiowave range. A number of investigations are known to be devoted to the development of the model of atmosphere dispertion in wide frequency band. That was also reflected in a number of overview papers related to centimeter and millimeter waves propagation [e.g.1].

But recently during experimental investigation of millimeter range surface communication line band properties it has been discovered that in some cases the atmosphere shows properties of a dispersion media, and the value and variability of the dispertion sufficiently exceed theoretic estimations and cannot be explained by the known phenomena [2]. The measurements have been carried out in 1 GHz frequency band near 37 GHz carrier frequency on 13 km long surface direct visibility path. Dispertion effects having no direct relation to atmospheric gases polarisation or hydrometeors and underlayer surface influence have been found. The revealed dispertion may sufficiently limit the operation of wide band communication lines [2] and high resolution systems. The measurements have been carried out by the phase invariant method in wich the measured value of phase invariant $\Delta\varphi$ is dispersion measure [2,3] and is equal.

$$\Delta\varphi = 2\varphi_0 - \varphi_1 - \varphi_2 , \qquad (1)$$

where $\varphi_0, \varphi_1, \varphi_2$ are phases of received modulated sensing signal discrete spectrum component, corresponding to the following frequencies: ω_0 – to the carrier frequency, $\omega_1 = \omega_0 - \Omega$ – to the lower side component and $\omega_2 = \omega_0 + \Omega$ – to the upper side component (Ω is modulation frequency). Phases included into (1) are

$$\varphi_i = \omega_i n(\omega_i) R c^{-1}, \qquad (2)$$

where i = 0,1,2 are indexes corresponding to the frequencies of signals making sensing signal spectrum; R is a distance between a transmitter and a receiver, c is a velocity of light in vacuum. If follows from (1) and (2) that in absence of dispertion $\Delta\varphi = 0$. The measurements carried out under the conditions of clear weather (in abcsence of hydrometeors) revealed the presence of daily and seasonal variations of $\Delta\varphi$ quantities and consequently the dispersion value. In Fig.1 average seasonal diurnal $\Delta\varphi$ variations are presented. The x axis is the time of day in hours. The y axis is $\Delta\varphi$ value measured in degrees. Curves corresponding to winter,

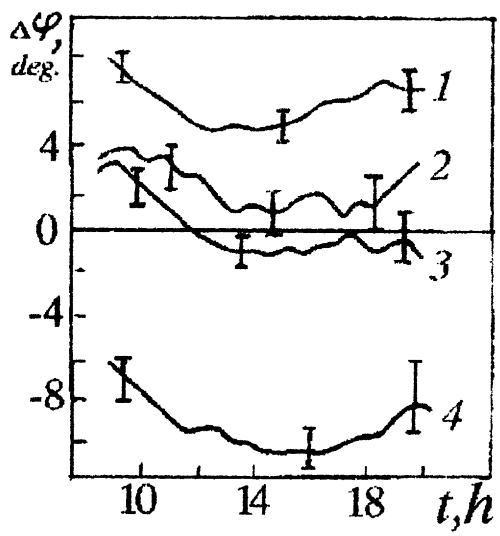

Fig.1 Average seasonal diurnal phase invariant variations

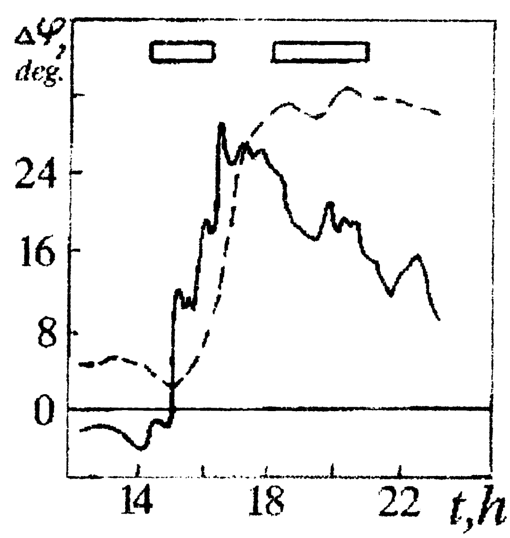

Fig.2 $\Delta\varphi$ values measurement results
——— in case of rain fall out
- - - in case of cold front motion

spring, autumn and summer seasons are marked by the number 1,2,3,4. A considerable growth of $\Delta\varphi$ values up to $+20...+30^\circ$ has been observed during the rain fall out in warm season and with the motion of cold atmospheric fronts in cold season. In Fig.2 typical measurements results in case of rainfalls in summer and cold front motion in winter are presented [2]. Temporal position of rains are marked by rectangles. Extreme $\Delta\varphi$ values were measured [2] in winter with the motion of cold atmospheric front ($\Delta\varphi = +64^\circ$) and in the beginning of summer under stable clear weather with the air temperature up to +30°C ($\Delta\varphi$ = -24°). These results appeared to be unexpected as they could not be described within the known dispertion models. Thus, estimation of molecular oxygen and steam absorption lines influense under the air temperature of +30°C have shown that in the frequency range used in [2] phase invariant in experimental commumication line does not exceed +0.16°. Direct influence of the earth surface on the measurements accuracy have been determined experimentally in paper [2] and estimated at $\Delta\varphi = \pm 1°$.

The aim of this paper is to ascertain physical reasons for earlier revealed dispertion effects in case of millimeter wave propagation in surface direct visibility channel and to develop dispertion model describing the effects found in experimental communication line.

3. PHENOMENOLOGY

The phenomenological model of ground-based channel of radio wave propagation of mm wave range in line-of-sight range, which explains dispersion effects, measured in [2], is presented in the paper. The known data about the spatial structure of ground-based atmosphere and radiowave propagation lie in the model basis.

It has been shown in the papers [4-9] and some others, that regular nonlinear dependence of N value on the altitude h over the ground surface is inherent to ground-based atmospheric layer. This nonlinear structure of $N(h)$ vertical profiles, is caused by the distinctions of meteorological elements distribution and is subjected to regular 24-hourly and seasonal variations [10]. 24-hourly variations of $N(h)$ profiles in the layer with altitude up to h = 100m, averaged over the seasons (for summer and winter) and typical for Russia, are plotted in Fig.3. The profiles were constructed by the experimental data from paper [9].

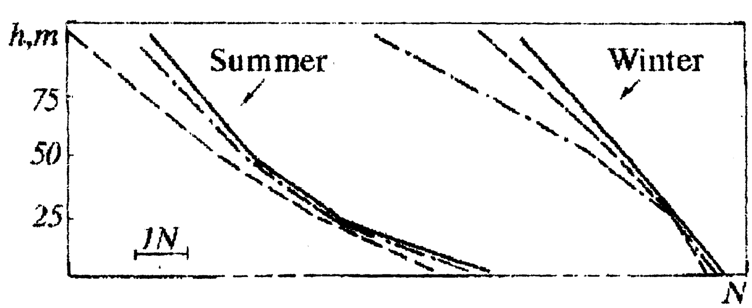

Fig.3 24-hourly variations of N(h) profiles, average over the season of the year
– – – – 6 a.m., ———— 2 p.m., – · – · – 6 p.m.

N unit is connected with N value by relation $N_{exp} = (N - 1) \cdot 10^6$. In order to stress the profiles' characteristic feature, which is essential to our analysis, the profiles were constructed from the point $h = 25$ m. In this case only time variations of index refractivity gradients values $g = dN / dh$ in the corresponding atmospheric layers were taken into account. Therefore the horizontal axis has no graduation as to value of N_1. It is essential that, the curves which represent the "summer" type of the profile $N(h)$ are concave and the curves which represent the "winter" ones are convex, i.e. these profiles have different signs of the second derivatives $d^2 N / dh^2$. It also follows from Fig.3 that for ground-based channels of radio wave propagation of mm wave range in the line-of-sight range it is characteristic the situation, when the scale of regular non-linear variations of media properties, which is transverse to the wave propagation direction is comparable with the Fresnel zones dimensions. For example, in 8-mm wave range the diameter of Fresnel zones $d = \sqrt{\lambda r}$ is equal by the order to 10 meters, here λ denotes radiation wave length.

Let's consider the mechanism of dispersion advent over radio wave propagation in the atmosphere with non-linear $N(h)$ profile. The qualitative behaviour of the propagation media in dependence on $N(h)$ profiles type and signal frquency is plotted in Fig. 4. Fig. 4a corresponds to the "summer" type of the profile and Fig. 4b corresponds to "winter" one.

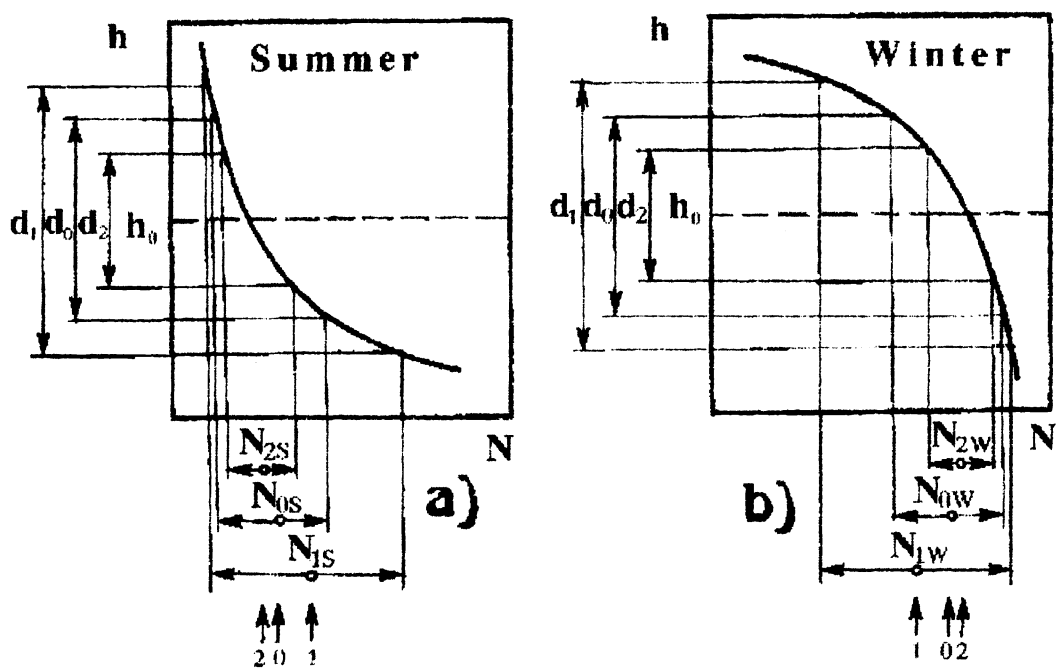

Fig.4 Atmospheric index refractivity variations in dependence on nonlinear profile N(h) type and signal frequency.

Let the axis of the space domain, which is essential under radio wave propagation passes through the point h_0. The diameters of the same name Fresnel zones are denoted by indexes d_0, d_1, d_2. These zones, according to presented in [2] measurement method of phase invariant values, correspond to signals with frequencies ω_0, ω_1, ω_2. The average values of variation ranges of N values within these zones for "summer" and "winter" profiles are denoted by N_{0s}, N_{1s}, N_{2s} and $N_{0\omega}$, $N_{1\omega}$, $N_{2\omega}$, correspondingly. For vizualization, in the bottom of each figure by the vertical arrows marked by digits 0, 1, 2, it is shown the location of these average values along the N axis. Inasmuch the dimensions of the same name Fresnel zones are not coincide with each other on different frequencies, the ranges of N values variation within such zones are not equal to each other and owing to nonlinearity of $N(h)$ profiles these ranges and their average values are shifted as to each other. Therefore, in this case signals with different frequencies propagate in the medias with different N values, i.e. the dispersion, caused by non-linear structure of $N(h)$ profiles occurs, or one can say about the dispersion, caused by the spatial structure of atmospheric ground-based layer. One can see from the Fig. 4 that with increase of the profiles nonlinearity rate (i.e. their second derivatives $d^2 N / dh^2$) the dispersion value will increase and in the case of linear $N(h)$ dependence (i.e. $d^2 N / dh^2 = 0$) such dispersion doesn't occur. This circumstance is connected with the fact, that the ranges of N values variation within the same name Fresnel zones are not shifted as to each other and their average values coincide by the value and are equal to $N(h_0)$ – index refractivity, determined from well known classic representations [11] at the altitude h_0. It is obvious that similar effects will be observed in the case of non-linear distribution of N values in horizontal direction (for example, in cloud cover).

Thus, if the parameters of propagation media vary in dependence on coordinates in the directions, transversed to the direction of wave propagation, such media is a dispersive one.

To distinguish the above mentioned dispersion advent mechanism from other known causes, which induce it's appearance, we shall use for this mechanism the term "spatial dispersion". Presented phenomenology enables to determine some properties of spatial dispersion and to show it's place in the general problem of wave propagation, and also to explain the experimental results, considered in [2]. In the futher development we shall take into account the spatial variations of N value only in vertical direction, inasmuch for ground-based atmospheric layer, where the radio links of line-of-sight range are located, dependence of N value on the altitude is most essential [4].

4. SPATIAL DISPERSION PROPERTIES.

Consider some spatial dispersion properties, which may essntially effect on the radio wave propagation in the ground-based atmospheric layer.

It follows from phenomenology that the spatial dispersion occurs only in the case of non-linear dependence of propagation media index refractivity value on coordinates, transversed to the direction of propagation. In application to wave propagation in the ground-based atmospheric layer this spatial dispersion property exhibits under non-linear distribution of N values along altitude h.

An important spatial dispersion property is the dependence of it's behaviour on the type of vertical profiles $N(h)$ nonlinearity. In the case of "summer" profile (Fig. 4a), the relation between average index refractivity values on frequencies $\omega_0, \omega_1, \omega_2$ one can describe by the inequality:

$$N_{1s}(\omega_1) > N_{0s}(\omega_0) > N_{2s}(\omega_2), \tag{3}$$

which represents anomalous character of the dispersion (N decreases with the increase of ω, i.e. $\omega_1 < \omega_0 < \omega_2$). In the case of "winter" profile $N(h)$ (Fig. 4b) corresponding inequality has a form :

$$N_{1w}(\omega_1) < N_{0w}(\omega_0) < N_{2w}(\omega_2), \tag{4}$$

and represents normal character of the dispersion (N increases with the increase of ω). Thus, over wave propagation in the atmospheric ground based layer the spatial dispersion may be either normal of anomalous, according to type of non-linear dependence of atmospheric index refractivity on the altitude h over ground surface. It is well known / see, for example [4] /, that non-linear dependence of N value on coordinates is peculiar to earth atmosphere and this cicumstance especially exhibits in the ground- and sea-based layers, in cloud cover, in atmospheric frontal partitions and in some other cases. One can contend that the spatial dispersion effects are inherent to the phenomena of radio wave propagation in the atmosphere. Thus, over the radio wave propagatien description the effective frequency dependent index refractivity $N_{eff}(\omega)$ must be used. This index refractivity $N_{eff}(\omega)$ one can represent as a sum of index refractivity, determined from well known classic representation $N_{cl}(\omega)$ (see, for example [11]), and the additional term, which appears owing to dispersion "spatial mechanism" $N_{sp}(\omega)$:

$$N_{eff}(\omega) = N_{cl}(\omega) + N_{sp}(\omega), \tag{5}$$

It follows from Fig. 4a that, in the case of anomalous spatial dispersion, the additional terms $N_{sp}(\omega)$ to $N_{cl}(\omega)$ value, which one can treat here as $N(h_0)$ value, are positive, i.e. the anomalous spatial dispersion leads to the increase of $N_{eff}(\omega)$ value in respect to $N_{cl}(\omega)$. In the case of normal spatial dispersion (Fig. 4b) the additional terms $N_{sp}(\omega)$ are negative and lead to decrease of $N_{eff}(\omega)$ value in respect to $N_{cl}(\omega)$. It follows from Fig. 4, that with the increase of ω, other things being equal, a contribution of $N_{sp}(\omega)$ into $N_{eff}(\omega)$ value will decrease, owing to decrease of Fresnel zone dimension. This property of spatial dispersion one can represent as follows :

$$\lim_{\omega \to \infty} | N_{sp}(\omega) | = 0 , \tag{6}$$

The qualitative variations of $N_{eff}(\omega)$ values in dependence on signal frequency and spatial dispersion character are plotted in Fig.5. The dependence of $N_{cl}(\omega)$ is depicted by solid line. By the same line we shall depict the dependence of $N_{eff}(\omega)$ in the case of linear profile $N(h)$, because for this profile $N_{sp}(\omega) = 0$. By the dash line we shall depict $N_{eff}(\omega)$ dependence, when the effects of anomalous spatial dispersion occur over radio wave propagation. The dependence $N_{eff}(\omega)$ in the case of normal spatial dispersion is shown by dash-dott line.

From the considered phenomenology it follows such evident property of the spatial dispersion, as N_{sp} value dependence on the range z of radio wave propagation in the atmosphere. Inasmuch, over the decrease of z value the Fresnel's zone dimension also decreases, the contribution of N_{sp} value will decrease (Fig. 4). Note that N_{cl} value in the expression (5) doesn't depend on the range z and is determined by the composition and the state of the atmosphere in measuring point and in general case also depends on frequency [4, 11].

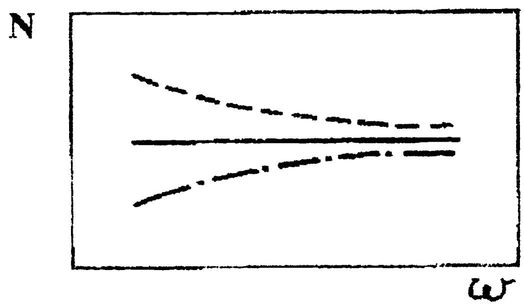

Fig.5 $N_{eff}(\omega)$ dependence in the case of - - - - anomalous and - · - · normal spatial dispertion, ——— $N_{cl}(\omega)$ dependence

Thus, the spatial dispersion phenomena is inherent to radio wave propagation in the atmosphere and in particular to propagation in ground- and sea-based layers. This dispersion may be either normal or anomalous. The contribution of the spatial dispersion to general atmospheric dispersion decreases with the signal frequency increase and decrease of radio wave propagation channel extent.

5. MEASUREMENTS RESULTS AND DISPERSION MODEL

The experimental investigations, which were carried out on a ground-based line-of-sight range path in 8-mm wave range, confirmed the phenomenology of spatial dispersion, presented in this paper. The results of mesurements are presented in [2]. It is shown that the brought out effects essentially impact on the band width of the radio link. The main results of above mentioned measurements from paper [2] are plotted in Fig. 1 and Fig. 2 for convenience of the explanation of these experiments.

Let's show the connection between the changeability of measured values of phase invariant $\Delta\varphi$ (expression (1)) and the spatial dispersion properties. Let δ is an increment of index refractivity with signal frequency increase from ω_0 to ω_1 (Fig.4), then index refractivity increment decreases with the signal frequency decrease from ω_0 to ω_1, owing to nonlinearity of N(h) profiles one may write as $\varkappa\delta$, where $\varkappa > 1$. Let's express N_2 and N_1 values by the increments δ and $\varkappa\delta$ relatively to N_0. From relations (1) and (2) one can obtain that in the case of anomalous dispersion (Fig. 4a) $\Delta\varphi$ values, with accuracy up to coefficients, are equal:

$$\Delta\varphi = \delta(1 - \varkappa), \tag{7}$$

and take negative values ($\varkappa > 1$). In the case of normal dispersion (Fig. 4b) one can obtain:

$$\Delta\varphi = \delta(\varkappa - 1), \tag{8}$$

In this case $\Delta\varphi$ are positive ($\varkappa > 1$). Besides, it follows from Fig. 4 and relations (7) and (8), that with increase of the profiles nonlinearity rate, the spatial dispersion value will increase, i.e. δ and $\varkappa$ values, and therefore $|\Delta\varphi|$ will also increase.

Thus, positive values of phase invariant correspond to the normal dispersion and negative to anomalous one. Greater phase invariant absolute value corresponds to greater dispersion.

The characteristic feature of experimental data, presented in Fig. 1, is the presence of extremums, located within the interval between 3 and 4 o'clock p.m. 24-hourly variations of phase invariant $\Delta\varphi$ values, averaged for winter season, occupy the region of positive values and for summer season, corresponding values occupy the region of negatives. In spring and autumn $\Delta\varphi$ measured values are close to zero. Let's compare these data with 24-hourly variability of $N(h)$ profiles (Fig. 3), which are also averaged over the seasons of the year. According to phenomenology of spatial dispersion advent it is shown that atmospheric ground-based layer with profile $N(h)$ (Fig. 3, Fig. 4a), which is characteristic for summer clear weather is a media with anomalous spatial dispersion and $\Delta\varphi$ measured values are negative (see, Fig. 1, curve 4). In the case of $N(h)$ profile (Fig. 3, Fig. 4b), which is characteristic for winter clear weather, the ground-based layer is a media with normal dispersion (see Fig. 1, curve 1). In spring and autumn the ground-based $N(h)$ profiles are close to linear ones [9]. As it was shown in the case of linear $N(h)$ dependence the spatial dispersion is absent and $\Delta\varphi = 0$. This fact is confirmed by the measurement results (Fig. 1, curves 2,3), when measured values $\Delta\varphi$ are close to zero. 24-hourly variations of values $\Delta\varphi$ are connected with 24-hourly variations of the profiles $N(h)$ by the next manner. In summer afternoon profile $N(h)$ (Fig. 3, solid line) has more expressed non-linear structure than in the morning or in the evening. By that spatial dispersion and consequently $|\Delta\varphi|$ have greater values (Fig. 1, curve 4). In winter one can observe the inverse situation. In the afternoon non-linear properties of profile $N(h)$ (Fig. 3, solid curve) are more pronounced than in the morning or in the evening. Smaller spatial dispersion and smaller values of phase invariant correspond to this time. This fact occurs in the measurement results presented in Fig. 1 (curve 1).

Thus, proposed spatial dispersion advent mechanism permits to explain on a qualitative level a 24-hourly and seasonal variability of measurement results, obtained under clear weather. The peculiarity of measurement results which carried out over the raintalls in summer (Fig. 2, solid curve) is a time delay (near 50 minutes) of the moment of measured $|\Delta\varphi|$ value change from negative to positive relative to the beginning of rain and further increase of this value to $+20^0 \ldots +30^0$. In the framework of proposed spatial dispersion advent mechanism it can be explained as follows. It is well known that [4,10,12] in atmospheric ground-based layer after rainfall the summer type of profile $N(h)$ (Fig. 4a) transforms to winter one (Fig. 4b). This fact occurs owing to compensation of humidity deficit in the atmospheric upper layers by the intensive evaportation from humid and heated surface. According to spatial dispersion phenomenology this fact leads to changing of spatial dispersion character: anomalous dispersion changed into normal and correspondingly negative values of measured value $|\Delta\varphi|$ change to positive ones. By that, value $|\Delta\varphi|$ is determined by nonlinearity rate of new profile $N(h)$. The vertical velocity of water vapours turbulence diffusion (near 1 m per minute [12]) and radio waves propagation channel altitude over ground surface (near 50 m [2]) can easily explain the reason and value (near 50 minutes) of time delay changing moment of value $\Delta\varphi$ from negative to positive relatively to rain beginning.

Thus, experimentally obtained change in the character and value of dispersion at rainfall in atmospheric ground-based layer may be explained in the framework of proposed spatial dispersion advent mechanism. The proposed mechanism allows to show both of qualitatively and quantitatively dynamics of physical processes in the atmospheric ground-based layer.

Under the conditions of cold atmospheric fronts motion sufficiently non-linear winter type profiles $N(h)$ (Fig. 4b) up to inversion ones have been established [4,8,10]. According to phenomenology of dispersion advent atmosphere with the profile of such type is a media with normal spatial dispersion. Positive values of measured value $\Delta\varphi$ correspond to that dispersion. The greater profiles $N(h)$ nonlinearity rate in a frontal partition causes a greater value of spatial dispersion and correspondingly greater values of phase invariant relative to the standart atmosphere. Such variaibility of values $\Delta\varphi$ which follows from phenomenology of spatial dispersion and processes in ground-based atmosphere under cold atmospheric fronts motion is prove to be true by the measurement results [2]. In Fig. 2 dott line represent the typical measurement results of $\Delta\varphi$ value under cold atmospheric fronts motion in winter. Usual for winter clear weather $\Delta\varphi$ values from interval $+4^0 \ldots +8^0$ increased up to 32^0 under cold atmosphere front motion. In the powerful cold fronts this increase reached $+64^0$, according to [2].

Thus, the results of experimental investigations carried out in winter with cold atmospheric fronts motion are explained in the framework of proposed spatial dispersion advent mechanism of radio wave propagation in ground-based atmospheric layer.

From considered phenomenology the spatial dispersion phenomena and it's properties confirmed by experimental investigations one must use effective index refrectivity while discribing radio waves propagation. This index refractivity has a form (5). The second term in this relation is undefined. It turns out that dependence $N_{eff}(\omega)$ in the framework of conditions of experimental work [2] may be aproximated by the function

$$N_{eff}(\omega) = N_{cl}(\omega) - 1.4\,\Delta\varphi\,(\omega_2\,\omega^{-1})^{1.55}. \tag{9}$$

According to representation (5) the second term describes the value $N_{sp}(\omega)$ variability via measured $\Delta\varphi$ values and frequency ω. This variability according to (6) is described as to maximal frequency ω_2 in the sounding signal spectrum, used in [2] (ω = 37.5 GHz). This fact constrains frequency interval of expression (9) applicability. The value $N_{cl}(\omega)$ is calculated in the framework of known models of atmospheric dispersion [11] and defines N in dependence on of atmosphere gases composition and state with due regards to impact of dielectric permeability rotation part of water steam and magnetic molecular oxygen permeability. The rotation part depends on ω. Expression (9) qulitatively and quantitatively describes dispersion effects wich were discovered in [2]. $N_{eff}(\omega)$ calculated values satisfy to measurement results [2].

A phenomenology which explains the reasons of spatial dispersion advent and relation (9) which describes frequency dependence of index refrectivity of experimental line-of-sight range radio link in millimeter wave range we shall consider as phenomenological model of radio waves dispersion in atmospheric ground-based layer.

In response of investigations carried out were shown the reasons of advent of radio waves dispersion effects in milimeter wave range over propagation in the line-of-sight range ground-based channel. All these effects were discovered experimentally. It was shown that if in directions transversed to radio wave propagation direction the media parameters depend on coordinates in non-linear form, then such media is dispersive. The variability of nonlinear spatial structure of atmosphere leads to variability of observed spatial dispersion effects. In the framework of this phenomenology next facts are explained: seasonal and 24-hourly variations of dispersion; effect of atmospheric fronts and rainfalls; the reasons of spatial normal and anomalous dispersion advent ; the dependence of spatial dispersion advent on signal frequency and radio waves propagation range. It was proposed phenomenological model of dispersion of experimental radio link. This model was confirmed by measurement results.

All these investigations can be a base for radio wave propagation theory development and methods of attenuation adverse influence of atmosphere effects on the wide range communication systems performance, system state determination, etc.

The results of these investigations can be useful in acoustics, hydroacoustics, optics, where dispersion problems of propagation media are actual.

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